3D risk mapping: preparing learning material on the use of laser scanning for risk assessment of public infrastructure

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Abstract: This paper describes a case study on the use of laser scanning for deformation monitoring of an arch dam of a hydroelectric power plant. The dam is about 400 m long and 100 m high with a maximal deformation of about six centimeters due to the changes in the water load during the year. The main purpose of this work is to prepare learning material for the European Leonardo da Vinci Project called '3Driskmapping', with the aim to create an e-learning platform for the use of 3D terrestrial laser scanning techniques for risk characterization of our built environment. The resulting package will consist of a theoretical part and a number of case studies for the hands-on training.

Keywords: Hydroelectric dam, Laser scanning, Trimble GX 3D, deformation, data acquisition, tutorial, 3D Risk Mapping, registration, geo referencing, meshing, differential model

1 Introduction

1.1 '3Driskmapping' case study

The aim of the project called '3DRiskmapping' which is co-financed by the European Leonardo da Vinci Project is to create an e-learning platform for the use of 3D terrestrial laser scanning techniques for risk characterization of our built environment.

The deliverables of the project include a number of 'ICT-supported training tools' that can be used and adopted by academic institutions in their current and future curriculum. The resulting package will consist of a theoretical basis on laser scanning and laser scanning data processing completed with a number of case studies in the form of online tutorials, lesson e-books and a decision flowchart for procuring 3D spatial information surveying projects with laser scanning [Van Genechten at al., 2007].

The main purpose of the work described below is to prepare learning material for the hands-on tutorial part of the project based on a real-life case study.
The chosen case study focuses on the use of laser scanning for risk assessment of public infrastructure, i.e. for the deformation monitoring of an arch dam of a hydroelectric power plant.

1.2 Hydroelectric power station – Arch dam

Hydroelectric Power Stations utilize the potential energy of dammed water to drive a water turbine and a generator to produce electricity. Pumped storage hydroelectricity is a method to produce electricity to supply high peak demands by moving water between reservoirs at different elevations. A mountain pumped-storage plant consists of a higher reservoir (situated in the mountains) and of a lower reservoir with the power building (e.g. in the valley). They are connected by a pipe with a diameter of some meters and with a difference in the height of several hundred meters. The water of the lower reservoir can be pumped back in the higher reservoir when the demand of electricity is low and therefore the price of electricity produced by other power plants, like nuclear plants is low.
A reservoir is created by one or several dams that are used as a barrier across flowing water to obstruct the flow. It can be made of stones, earth and clay, a so called embankment dam, or it is made of masonry. Masonry dams are of either the gravity or the arch type. An arch dam is a thin, curved concrete or masonry dam structure which is curved upstream in plan so that the force of the water against it squeezes the arch, compressing and strengthening the structure and pushing it into the ground. An arch dam is most likely used in a narrow site in a mountainous area with steep walls of sound rock [Wikipedia, 2007]. Arch dams can reach heights to several hundreds of meters and they have partially an elastically behaviour in case of external variable loads.

1.3 Origin of deformation

The filling level of a mountain reservoir is not constant but fluctuating, whereas the fluctuation can be divided in short frequent and large frequent changes in the filling level. The short frequent fluctuation with a period of one day is e.g. of small amount, whereas the large frequent one appears seasonal and is of much higher amount due to missing water feeding during the winter or dry periods. Because of this variation of the filling level the resulting pressure on the dam's surface differs and causes different loads on the dam body. This leads to an elastic deformation of the arch dam structure with a change in shape.

Plastic deformation may occur only in the first years after the completion of a dam because of structural settlement and soil consolidation of the ambient bedrock.

1.4 Deformation measurement

The deformation of hydroelectric dams will be monitored periodically due to the enormous risk for human live in the case of a dam failure. Typically the monitoring is done by surveying single points on the dam's surface (e.g. on the crest of the dam) or by measuring traverses along surveying gangways that are located at different levels inside the dam. Furthermore the dams may be equipped with traditional sensors like strain gauges and perpendicular measuring systems to observe permanent the relative horizontal dislocation of the crest (inclinometers).

The purpose in applying terrestrial laser scanning for monitoring the dam movements is to measure the deformation on the surface of the dam not only in a few single points but in a dense raster with point information every few centimetres. Out of this point cloud a dense and accurate surface model can be generated which describes the actual surface. A comparison of two or more of such surface models from different dates is able to show the deformation of the entire surface. The results contain further relevant information, like if the deformation is homogenous all over the dam or if there is a local buckling. Further if there are zones with a higher risk factor for deformation which afterwards may be surveyed more frequently and with smaller equipment, like motorized total stations with automatic target recognition (TPS).

The advantages of determining the deformation of dam structures by comparing surfaces obtained from TLS point clouds are shown by various authors [Alba M. et al., 2006; Eling D., 2006; Hesse C. and H. Kutterer, 2006]. It was shown by Rudig [2005] that the application of NURBS algorithms for the surface representation offers the possibility to assess deformations of a dam surface of only 3mm. In his case study the distance between scanner and object was about 60 m and the accuracy of the measured single points was ±6 mm.

1.5 Site documentation:

Fig. 1: Arch dam of reservoir *Kops*

The surveyed object in this case study is the arch dam of the reservoir *Kops* (Fig. 1), situated at an altitude of 1800 m above MSL within the mountain ridge *Silvretta* in western Austria. The reservoir belongs to the *Vorarlberger Illwerke AG*, which is the regional operating company of hydroelectric power stations of the province of Vorarlberg. The double curved arch dam is about 400 m long and 100 m high and is made of reinforced concrete.

The operating company maintain surveying pillars around the reservoir and on the crest of the dam. In 2001 a GOCA - GPS-Based Online Control and Alarm – system has been tested to monitor the crest movement. Via GPS rovers placed on these pillars it was possible to observe movements of the crest of the dam [Feldmeth et al., 2002].

The deformation of the dam is permanently monitored by the operating company using traditional techniques (see 1.4). A perpendicular measurement systems works with one or more inclinometers (perpendiculars) in vertical ducts reaching from the crest to the base of the dam.

Four horizontal gangways are situated inside the dam body including survey pillars at every 25-30 m. High precision gyrotheodolite observations and invar wire measurements are used to determine dislocations of the pillars in these gangways. These measurements shall be conducted every half a year to determine the actual deformation of the dam (Fig. 2).

Since structural settlement and soil consolidation has finished the remaining elastic deformation of the arch dam results in a change in shape of the structure of less than 8cm centimetres.

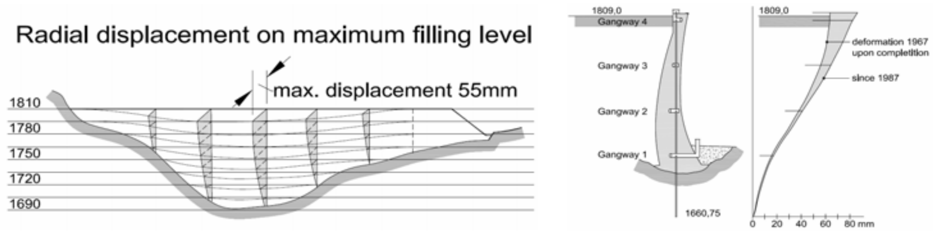


Fig. 2: Deformation obtained by inclinometer and geodetic measurements inside the dam

2 Goals and Deliverables:

The arc dam of the *Kops* reservoir was measured twice at two different times with the aim to deliver a complete dataset for the hands-on training of the European Leonardo da Vinci Project called ‘3Driskmapping’.
Thus, these two real world data sets offer the possibility:

- to train the entire laser scanning process of session planning, scanning and post processing in a detailed and complete way
- to carry out risk assessment by comparing the deformed dam surfaces of two different reservoir filling levels

Issue of the case study: Understand and realize terrestrial laser scan measurements of the dam’s surface for deformation assessment by optimizing the scanning proces*s:*

- *Definition of the maximum distance between dam and scanner:* Define the maximum scanning distance in relation to the number of scanstation positions taken in account the required homogeneous accuracy.
- *Determination of minimum angle between surface and laser beam:* Calculate the minimum angle between laser beam and surface with a maximum of accuracy.
- *Optimize the kind of targets:* Define optimal target objects for different scanning distances.

Furthermore, it is an aim of this case study to calculate the deformation amount and to study whether the deformation is homogenous all over the dam or if there is a local buckling and if there are zones with higher risk factors for deformation.

Outcome:

- Two digital terrain models (DTM’s) representing the dam’s surface at two different reservoir filling levels
- Differential model of these DTM’s describing the deformation (displacement vectors in a dense raster)

3 Methodology

The measurement campaigns were realized mid of April 2007 (reservoir with low filling level) and mid of September 2007 (reservoir almost at maximum filling level). At the time of the first measurement the reservoir was already filled for one third. An earlier date with a lower filling level would have been better to detect the total amount of deformation, but strong snowfall and avalanche risk in spring 2007 impeded to work at the site.

3.1 Workflow

In the following subsections tasks related to the planning, field work and post processing phases are described.

3.1.1 Session planning

The application of TLS in high alpine regions requires a sound session planning. The mountainous topography with cliffy and steep slopes hinders the stationing of the scanner. Scanning distances of more than 200 m on the one hand and steep angles of incidence of the scanning beam on the other hand requires a long range scanner with high accurate distance and angle measurement to fulfil the requirements of hydroelectric dam monitoring. Therefore, the Trimble GX 3D terrestrial laser scanner was chosen for this project.

Before leaving the office for fieldwork any step of the workflow of data acquisition in the field should be defined and checked and rechecked. To optimize this workflow definition a detailed simulation of the field work should be done. In this case the simulation tool of the Autodesk® product CIVIL 3D 2007™ has been applied using a geometric model of the field of view of the scanner (360° x 60°) and a 3D model of the site as input data. This 3D site model was created in two steps: First a 3D-CAD-model of the dam was created based on existing drawings and plans (Fig. 3). Secondly a DTM of 1x1 m (based on airborne LIDAR data from the government) were used for the surrounding terrain.

Based on this 3D model of the site (Fig. 4) it is possible to optimise scanstation positions and scanning angles for the field work.

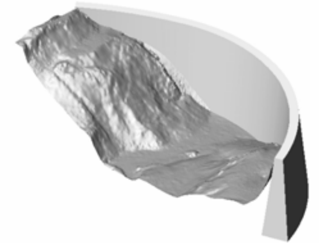


Fig. 3: 3D-CAD model of the dam

Fig. 4: 3D model of the entire site

The intersection of the field of view model of the scanner with the 3D site model delivers the visible and observable dam surface section at the corresponding scanstation position. Further, the maximum scan ranges and the angles of incidence of the laser beam on the dam surface will be calculated. Information about possible shadowing due to vegetation can be derived by visual interpretation of a geo-referenced orthophoto of the site. So it is possible to decide already in the office whether the scanstation position is suitable or not.

For most of the scanstation positions the simulation showed scanning ranges between 170 m and 350 m due to the vertical operating angle of only +/- 30°. Scanning so close at the maximum scan range of the system (200 m to 35% and 350 m to 90% reflective surface [Trimble, 2007]) would result in difficulties like an enormous increase of the scan time, gaps at low reflective dam surface sections, difficulties in target identification etcetera.

A solution was found by turning the whole scanner for 90° (Fig. 8). The resulting effect is that the field of view changes to 60° x 360° (Hz x Vt). Now it is possible to scan the whole height in one section close to the object. After finishing the scan of such a “vertical section” the scanner can be turned easily to scan the adjacent “vertical section” by using an adapted tripod mounting.

Altogether seven scanstation positions were defined along the base of the dam with resulting scan ranges of 20 up to 180 m (Fig.5).

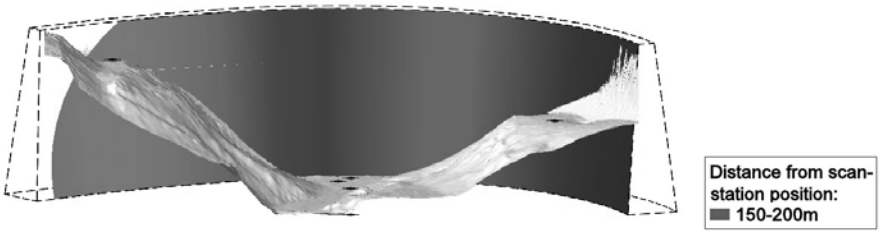


Fig. 5: Simulation of scan ranges; standard mounting of the scanner; axis not tilt
➔ scan ranges between 160 m and 240 m

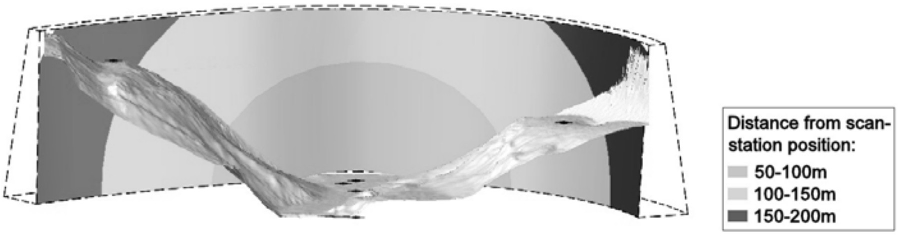


Fig. 6: Simulation of scan ranges: standard mounting of the scanner; z-axis 30° inclined ➔ scan ranges between 70 m and 190 m

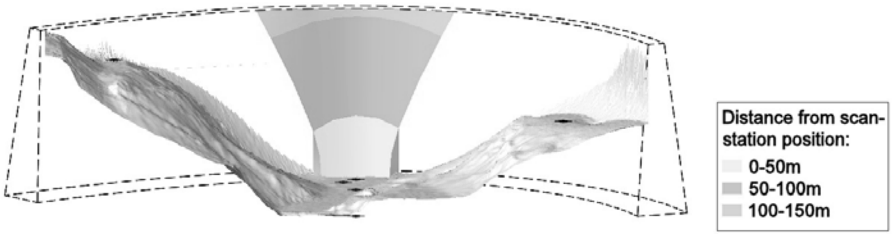


Fig. 7: Simulation of scan ranges: scanner mounted vertically;
➔ scan range: 35 m – 110 m; scan width limited to 60° (vertical scanner aperture)

3.1.2 Field work

The scanner has been situated in the scanstation position defined in the session planning. Trimble Point Scape 3.2 was the used control unit software for the scanner, running on Colibri X6 tablet PC. Up to eight targets were distributed around the scanner at each scanstation. Trimble spheres with a diameter of 76.20 mm were used as targets near the scanner (up to 50 m of distance). Spheres with a diameter of 239.70 mm were used to enable target measurements at the remote areas of the scanned sectors (Fig. 9). It is imperative to use these remote targets at the outer limit of the sections, like the dam crown. It ensures a stable georeferencing of the scanned point cloud and increases significantly the accuracy. The position of the targets were determined out of TPS measurements using a Leica TCRP 1202, which was mounted on survey pillars from a surrounding geodetic network.

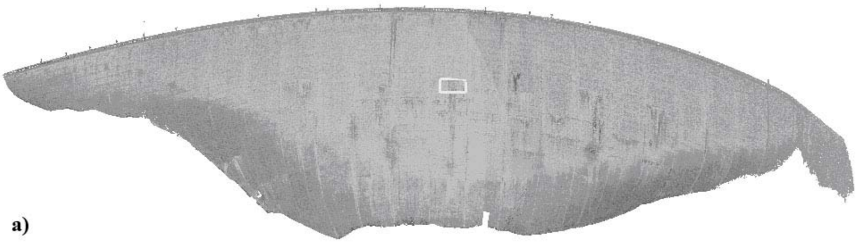
The atmosphere near the surface of the dam is extremely inhomogeneous due to the heating of the concrete surface of the dam by the sun and the turbulences of the ascending air. This creates deflections of the laser beam of the scanner as well as of the total station and leads to errors of some millimetres.

Fig. 8: Scanner mounted vertically (bracket 90° tilt)

Fig. 9: Target spheres for short range and long range measurements: Diameters, 76.2mm and 239.7mm, respectively

3.1.3 Post Processing

The point clouds were post processed with the Trimble software *RealWorks Survey 6.0*. Automatic point filtering, manual editing of point clouds, like erasing of measurements of insignificant zones as well as registration and georeferencing are tasks of the point cloud post processing. Within this project only the target-based registration has been applied to avoid possible errors of the cloud-based registration process, like misinterpretation when matching the common parts of the two point clouds. The coordinates of the targets were calculated with the surveying and civil engineering software *rmdata* applying an adjustment computation. With the known coordinates of the targets, the point clouds could be georeferenced with a medium accuracy for the targets of less than 10 mm. Finally surface models were calculated for the two epochs using the Mesh creation tool of RealWorks Survey 6.0 (**Fehler! Verweisquelle konnte nicht gefunden werden.**).



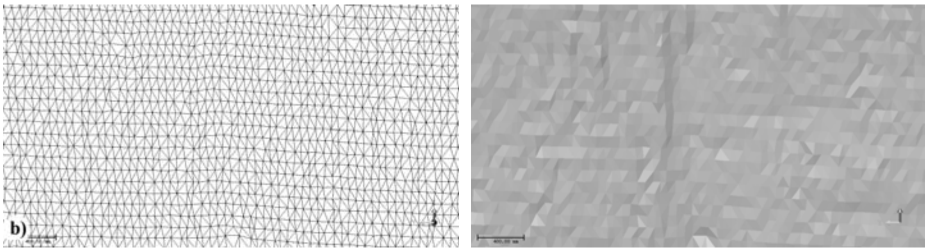


Fig. 10: a) Georeferenced point cloud of the entire dam; b) triangulated mesh of highlighted section: wire frame representation (left) and textured surface (right)

3.2 Tutorial

Out of this case study a tutorial for the Leonardo da Vinci Project 3D Risk Mapping has been developed. In the following part a summary of his content is given:

The tutorial first gives a short introduction and description of a hydroelectric power plant and explains that a periodically surveying job is needed because of the risk of a deformation or an eventual break of the construction.

Afterwards it describes the need of a good session planning because of the rough mountainous topography with extreme climatic conditions. This session planning has been done by simulating the scanning situation as described above. So it was possible to determine the scanstation positions before starting the fieldwork, in consideration of the scanner, the object and the topography characteristics.

Further a short market report of scanner systems shows the properties of four different scanners. In the chapter data acquisition the different kinds of targets are described, the reference coordinate system is assessed, the used platforms are described and the scanstation positions are determined. Moreover the chapter data processing gives a guideline for the program RealWorksSurvey. This guideline deals in detail with issues on how to register and how to georeference the acquired point cloud, how to filter them and how to make a meshing process. This guideline is also available as "learning step-by-step video".

4 Results and conclusion

The final goal of this project is to investigate whether or not it is possible to measure dam deformations with terrestrial laser scanning. First results are available.

Special scan station mounting and positioning was necessary due to the mountainous topography and the extraordinary dimension of the scanned object. Moreover additional targets in remote scan areas as well as meteorological data acquisition for determining proper parameters for atmospheric corrections were necessary to achieve the required accuracy. At the moment different methods for surface modelling are being tested, e.g. TINs, NURBS, to describe the dam surface. Finally the deformation of the dam is determined by comparing the surfaces of the two epochs as described by Rudig [2005].

It turned out, that terrestrial laser scanning is a promising technology for monitoring deformations of dam surfaces if scanner and scan configuration are appropriate.

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